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# FINITE SIZE CORRECTIONS IN MASSIVE THIRRING MODEL

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## ABSTRACT

We calculate for the first time the finite size corrections in the massive Thirring model. This is done by numerically solving the equations of periodic boundary conditions of the Bethe ansatz solution. It is found that the corresponding central charge extracted from the  $1/L$  term is around 0.4 for the coupling constant of  $g_0 = -\frac{\pi}{4}$  and decreases down to zero when  $g_0 = -\frac{\pi}{3}$ . This is quite different from the predicted central charge of the sine-Gordon model.

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In two dimensional field theory, there is a remarkable correspondence between the fermionic and bosonic field theories. This was first recognized by Coleman [1], and he proved that the sine-Gordon field theory and the massive Thirring model are equivalent to each other in that the arbitrary order of the correlation functions turn out to be the same.

Recently, however, Klassen and Melzer [2] argue that the equivalence between the sine-Gordon and the massive Thirring models may be violated at the finite size correction. They proved by using the perturbed conformal field theory that these two models are different in finite-volume energy levels, for example.

In this paper, we calculate the finite size corrections to the ground state energy. We solve numerically the equations of the periodic boundary condition in the Bethe ansatz solutions of the massive Thirring model [3-5]. The ground state energy can be expressed as

$$E_v = E_0 L - \frac{\pi \tilde{c}}{6L} + \dots \quad (1)$$

where  $L$  denotes the box size.  $\tilde{c}$  corresponds to a central charge at the massless limit [6,7].

The present calculation shows that the corresponding central charge  $\tilde{c}$  in the negative coupling constant regions (no bound states) is around 0.4 for  $g_0 = -\frac{\pi}{4}$  and that it becomes zero when  $g_0 = -\frac{\pi}{3}$ . These values can be compared with those calculated for the sine-Gordon field theory [8,9]. The central charge for the sine-Gordon field theory with the massless limit can be expressed as

$$c = 1 - \frac{6}{p(p+1)} \quad (2)$$

where  $p$  is an integer and is related to the coupling constant  $g_0$  as

$$g_0 = -\frac{\pi}{2} \left(1 - \frac{1}{p}\right). \quad (3)$$

In fig.1, we summarize the calculated central charge as the function of the coupling constant for the sine-Gordon model by Itoyama and Moxhay, and for the massive

Thirring model by the present calculations. One can see that the values of the central charge predicted for the two models are very different from each other.

It is, however, not very clear to us whether this difference may be related to a possible violation of the equivalence between the sine-Gordon field theory and the massive Thirring model at the finite volume energy as suggested by Klassen and Melzer.

Here, we briefly review the massive Thirring model whose lagrangian density can be written as [10]

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu\partial^\mu - m_0)\psi - \frac{1}{2}g_0 j^\mu j_\mu \quad (4)$$

with the fermion current  $j_\mu =: \bar{\psi}\gamma_\mu\psi$ . Choosing a basis where  $\gamma_5$  is diagonal, we write the hamiltonian as

$$H = \int dx \left[ -i(\psi_1^\dagger \frac{\partial}{\partial x} \psi_1 - \psi_2^\dagger \frac{\partial}{\partial x} \psi_2) + m_0(\psi_1^\dagger \psi_2 + \psi_2^\dagger \psi_1) + 2g_0 \psi_1^\dagger \psi_2^\dagger \psi_2 \psi_1 \right]. \quad (5)$$

The hamiltonian eq.(5) can be diagonalized by the Bethe ansatz wave functions  $\Psi(x_1, \dots, x_N)$  with  $N$  particles

$$\Psi(x_1, \dots, x_N) = \exp(im_0 \sum x_i \sinh \beta_i) \prod_{1 \leq i < j \leq N} [1 + i\lambda(\beta_i, \beta_j)\epsilon(x_i - x_j)] \quad (6)$$

where  $\beta_i$  is related to the momentum  $k_i$  and the energy  $E_i$  of  $i$ -th particle as

$$k_i = m_0 \sinh \beta_i. \quad (7a)$$

$$E_i = m_0 \cosh \beta_i. \quad (7b)$$

where  $\beta_i$ 's are complex variables.

$\epsilon(x)$  is a step function and is defined as

$$\epsilon(x) = \begin{cases} -1 & x < 0 \\ 1 & x > 0. \end{cases} \quad (8)$$

$\lambda(\beta_i, \beta_j)$  is related to the phase shift function  $\phi(\beta_i - \beta_j)$  as

$$\frac{1 + i\lambda(\beta_i, \beta_j)}{1 - i\lambda(\beta_i, \beta_j)} = \exp(i\phi(\beta_i - \beta_j)). \quad (9)$$

The phase shift function  $\phi(\beta_i - \beta_j)$  can be explicitly written as

$$\phi(\beta_i - \beta_j) = -2 \tan^{-1} \left[ \frac{1}{2} g_0 \tanh \frac{1}{2}(\beta_i - \beta_j) \right]. \quad (10)$$

From the definition of the rapidity variable  $\beta_i$ 's, one sees that for positive energy particles,  $\beta_i$ 's are real while for negative energy particles,  $\beta_i$  takes the form  $i\pi - \alpha_i$  where  $\alpha_i$ 's are real.

Since the Bethe ansatz wave functions diagonalize the hamiltonian, we demand that they satisfy the periodic boundary conditions (PBC) with the box length  $L$  [3],

$$\Psi(x_i = 0) = \Psi(x_i = L). \quad (11)$$

This leads to the following PBC equations,

$$m_0 L \sinh \beta_i = 2\pi n_i - \sum_j \phi(\beta_i - \beta_j) \quad (12)$$

where  $n_i$ 's are integer. Here, we note that we cannot take the anti-periodic boundary condition since it does not reproduce the boson spectrum in the positive coupling constant regions [5].

The parameters we have here are the box length  $L$  and the particle number  $N$ . In this case, the density of the system  $\rho$  becomes

$$\rho = \frac{N}{L}. \quad (13)$$

Here, the system is fully characterized by the density  $\rho$ .

We write the PBC equations for the vacuum which is filled with negative energy particles ( $\beta_i = i\pi - \alpha_i$ ),

$$\sinh \alpha_i = \frac{2\pi n_i}{L_0} - \frac{2}{L_0} \sum_{j \neq i} \tan^{-1} \left[ \frac{1}{2} g_0 \tanh \frac{1}{2}(\alpha_i - \alpha_j) \right], \quad (14)$$

where  $n_i = 0, \pm 1, \pm 2, \dots, \pm N_0$  with  $N_0 = \frac{1}{2}(N - 1)$  and  $L_0 = m_0 L$ .

In this case, the vacuum energy  $E_v$  can be written as

$$E_v = - \sum_{i=-N_0}^{N_0} m_0 \cosh \alpha_i. \quad (15)$$

In this paper, we have carried out the numerical calculations of the PBC equations. The numerical method to solve the PBC equations is explained in detail in ref.[5].

Now, the calculated vacuum energy can be parametrized as

$$E_v = E_0 L - \frac{\pi \tilde{c}(g_0)}{6L} + \dots \quad (16)$$

where  $\tilde{c}(g_0)$  corresponds to the central charge at the massless limit. In what follows, we call this  $\tilde{c}(g_0)$  as the central charge even though we are solving the massive field theory. It should be noted that the first term in eq.(16) can be evaluated analytically by taking the thermodynamic limit [3].

Since we can vary the values of  $L$  and  $N$ , we obtain the corresponding central charge  $\tilde{c}(g_0)$ . Although we have still rather small particle number ( $N \sim 10000$ ), we believe that the values extracted for the central charge must be reasonably reliable.

Now, we want to obtain the central charge  $\tilde{c}(g_0)$  at the field theory limit  $\rho \rightarrow \infty$ . In fig. 2, we show the calculated central charge  $\tilde{c}(g_0)$  as the function of the effective density  $\rho_0 = \frac{N_0}{L_0}$ . It is quite interesting to observe that the calculated central charge can be well parametrized by the following simple formula [11],

$$\tilde{c}(g_0) = A + B \exp \left( -\frac{\kappa}{\rho_0} \right) \quad (17)$$

where  $A$ ,  $B$  and  $\kappa$  are constants. Therefore, the field theory limit can be easily taken since we can let  $\rho_0$  infinity.

In Table 1, we show the values of  $A$ ,  $B$  and  $\kappa$  for some values of the coupling constant  $g_0$ . The central charge becomes  $A + B$  at the field theory limit. The

calculated values of the central charge are shown as the function of the coupling constant  $g_0$  in fig.1. We also plot the central charge calculated for the sine-Gordon theory by Itoyama and Moxhay [9]. As can be seen from the fig.1, the two values of the central charge are quite different from each other.

How can we interpret these differences ? The first possibility is that the two theories (sine-Gordon and massive Thirring models) are different from each other at the finite volume. We do not know whether this difference can show up as the central charge or not. However, a simple-minded physical intuition suggests that the central charge which should correspond to the heat capacity cannot be different if all the correlation functions of the two models are the same with each other. In this case, we should rather check the convergence of the perturbation expansions in Coleman's proof of the equivalence between the sine-Gordon and the massive Thirring models since it crucially depends on the convergence of the expansions. For the negative values of the coupling constant, we do not know whether this convergence is already verified or not.

The second possibility is that neither of the calculations are accurate enough to argue the difference between them. To this, we should comment on the accuracy of the present calculations. Since we have only the limited number of particles, we always face the criticism that the real nature (even though 1+1 dimension) must be with the infinite number of particles. We have varied the number of particles from 1000 to 10000. It seems to us that the extracted central charge may well be reliable to within a few tens of percents. At least, we believe that the calculation must be rather reliable for the coupling constant around  $g_0 = -\frac{\pi}{4}$  where the extracted central charge is not very small. On the other hand, the present calculation may involve somewhat large errors for the coupling constant around or smaller than  $g_0 = -\frac{\pi}{3}$  since the extracted central charge is

rather small. This is in contrast to the bound state problems [5,12-13] where there is some possibility of controlling the accuracy of the numerical calculations. However, the evaluation of the central charge involves rather complicated processes of extracting it since we have to obtain it from the term proportional to  $\frac{1}{L}$  in the vacuum energy. Therefore, the error bars of the calculations we have shown in fig.1 may well be still optimistic numbers.

Concerning the central charge of the sine-Gordon model, we do not know whether the central charge predicted by Itoyama and Moxhay can be taken to be exact or not. Here, we only make a comment on the *string* hypothesis in the massive Thirring model when they employ the thermodynamic Bethe ansatz [14]. As discussed in ref.[5,11], the *string* picture in the massive Thirring model in the positive values of the coupling constant turns out to be invalid in the sense that they do not satisfy the PBC equations. However, in the negative values of the coupling constant, we do not know whether there is a *string*–like solution that satisfies the PBC equations.

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Table 1

$\frac{g_0}{\pi}$	$A$	$B$	$\kappa$	$\tilde{c}(g_0)$
- 1/4	0.941	- 0.562	25	$0.38 \pm 0.09$
- 0.276	1.06	- 0.745	16.5	$0.32 \pm 0.05$
- 0.291	1.06	- 0.795	16	$0.27 \pm 0.06$
- 0.305	0.901	- 0.739	25	$0.16 \pm 0.07$
- 0.319	0.854	- 0.790	30	$0.06 \pm 0.04$
- 1/3	0.793	- 0.879	40	$- 0.09 \pm 0.10$

We show the values of  $A$ ,  $B$  and  $\kappa$  for some coupling constant  $g_0$  together with the  $\tilde{c}(g_0)$  at the field theory limit.

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